P-23: Neutron Science and Technology

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Introduction

The Neutron Science and Technology Group (P-23) carries out a synergistic program of basic and applied research in weapons physics, nuclear physics, and quantum information science. The common feature of this diverse set of efforts is the application of state-of-the-art techniques in particle and light detection and the recording of transient events.

Within the area of weapons physics, we participate in design and fielding of subcritical experiments, non-nuclear hydrodynamic experiments in support of above-ground experiments (AGEX-I), pulsed-power experiments, and archiving and analyzing data from past nuclear-weapons tests. Our fundamental research focuses on nuclear and weak-interaction physics and on astrophysical phenomena involving the detection of solar neutrinos and ultra-high-energy gamma rays. Applied research includes the development of quantum-information technologies, such as quantum computation and encryption (involving single-photon detection) and the application of imaging and neutron technologies to problems relevant to national defense or industry.

We conduct our research at local facilities such as the Los Alamos Neutron Scattering Center (LANSCE), Pegasus, Milagro (Fig. 1), and local firing sites, as well as at remote facilities like the Nevada Test Site (NTS) and the Sudbury Neutrino Observatory (SNO). All of these facilities are world class, offering the best available resources for our research. Of these facilities, only the Milagro

***Fig. 1** The Milagro detector is comprised of 723 photomultiplier tubes situated in a 5,000-m^2, 8-m-deep pond at an altitude of 8,700 ft. The photograph shows the pond before it has been filled with water, which will allow the Kevlar-bound photomultiplier tubes to extend towards the sky. Milagro should be able to detect the particle showers produced by very high-energy gamma rays as they enter the atmosphere.*

gamma ray observatory is owned and operated by P-23. We contribute to Laboratory programs in science-based stockpile stewardship (SBSS), accelerator production of tritium (APT), and energy research, as described below.

Weapons Physics and Science-Based Stockpile Stewardship

With the end of nuclear testing, SBSS has become the foundation of the Los Alamos nuclear-weapons program. Our knowledge of how complete nuclear weapon systems perform relies on data obtained from tests at NTS and test locations in the Pacific Ocean. Saving, analyzing, and documenting NTS weapons test data is crucial to the success of SBSS. P-23 shares responsibility for preservation and analysis of these data with other groups involved in these tests. In P-23, physicists and engineers who performed the original measurements are working to analyze and correlate the data of different events. In addition, new scientists are learning the technologies of making such measurements in case the need should arise for future underground tests.

The work of the group concentrates on analysis of pinhole neutron experiments (PINEX) imaging data and on neutron emission measurements (NUEX and THREX). These data complement the reaction history and radiochemical measurements made by other groups. As a whole, this research has provided a better understanding of the underlying physical processes that generated the data, and the comparison of results from different tests has allowed us to study systematically the behavior of nuclear explosives.

To ensure the success of SBSS in allowing us to certify the performance of our nuclear weapons in the absence of nuclear testing, P-23 is striving to develop better physics models that can be incorporated into computer codes to calculate explosive performance. Only by validating such codes with the existing NTS data will we be able to address with confidence the issues of aging and remanufacture of our stockpile weapons.

In addition to the analysis of NTS data, P-23 is participating in a series of experiments to explore weapons-physics issues of a more microscopic nature. In these experiments, we use chemical explosives and pulsed-power machines such as Pegasus to examine issues such as the EOS of shocked materials, formation and transport of ejecta from shocked surfaces, and growth of hydrodynamic instabilities. Our work includes a series of underground experiments involving plutonium at the U1a facility at NTS. These experiments employ a wide range of technologies, including gated visible imaging, gated x-ray imaging, holography, and infrared temperature measurement, to explore the physical phenomena. P-23 is currently developing fast infrared imaging technology, which will provide the ability to study freeze-frame dynamic motion in the infrared range. The data from all of these technologies allow us to better understand hydrodynamics of interest to the weapons program. As computer models are developed further, the data will allow us to benchmark the models.

Other weapons program work focuses on what happens to a weapon as its components age. NTS experiments and other previous weapons tests did not focus on this issue, and the data from these tests are not sufficient to assure the safety and reliability of the nuclear-weapons stockpile without nuclear testing. The SBSS program is intended to provide a scientific basis for addressing this and other assurance issues without nuclear testing. As part of this effort we have joined colleagues in other groups and divisions at Los Alamos National Laboratory, as well as from the Lawrence Livermore National Laboratory, to study the following issues:

- the performance of chemical explosives, including changes in performance as they age;
- the fundamental physics of plutonium, *e.g.*, the phonon spectrum;
- the temperature of materials undergoing hydrodynamic instabilities; and
- nuclear cross sections that are required for better analysis of radiochemical data from previous weapons tests.

For these studies we use neutrons from LANSCE sources, including moderated neutrons from the Manual Lujan, Jr., Neutron Scattering Center (MLNSC), moderated neutrons with tailored time-structure from the Weapons Neutron Research (WNR) Blue Room, and unmoderated neutrons from the WNR fast-neutron source. Neutron spectroscopy by time-of-flight techniques is central to all of these projects.

An important element of the SBSS program at LANSCE is hadron radiography. P-23 is supporting this effort with a cold-neutron radiography project at the MLNSC and by participation in the proton-radiography project. P-23 developed a cooled, charge-coupled device (CCD) imaging system with fast gating and image intensification for use in hadron radiography. The system was first applied to radiograph a low-density material encapsulated in a high-density casing using neutrons produced at the WNR in the 5- to 200-MeV energy range. The group has also collaborated with the Subatomic Physics Group (P-25) in the development of a pixellated, gas-amplification wire-chamber detector for hadron radiography. Our future work includes development of framing camera techniques to be applied to proton radiography. We propose to include a framing camera between the image intensifier and the CCD camera. This will enable the recording of four frames on each CCD and would increase the total number of frames to 28.

P-23 also supports the SBSS program by obtaining nuclear data at the WNR facility. At WNR, a large array of Compton-suppressed germanium detectors, known collectively as the GEANIE detector, is used to measure gamma rays from neutron-induced reactions. Our interests at present are in the ^{239}Pu(n,2n)^{238}Pu cross section, where different nuclear-reaction models give markedly different predictions, and in the nuclear structure area of "complete spectroscopy," where models of nuclear-structure symmetries and the transition from order to chaos in nuclear spectroscopy can be tested.

A critical, and currently limiting, component to a number of weapons program experiments is the need for better imaging technologies. Prior to the cessation of underground testing at NTS, the Laboratory (previously in J-12 and P-15, and then in P-23) developed an in-house capability to meet the advanced imaging needs for the Weapons Program's underground shots. Currently, the SBSS program has turned to above-ground experiments that are again placing ever increasing demands on imaging and other technologies. There is currently a need for an imaging sensor that can be gated (or shuttered) in the few-nanosecond to subnanosecond regime, can achieve a high frame (or data) transfer rate (up to 10^7 frames per second), has a high quantum efficiency (1% to 50%) and sensitivity (<10 photons per pixel detection), and covers the spectrum from visible light into the near-infrared regime (380 nm to 5 μm in wavelength). Such advanced imaging capability is not available commercially, and the technology for achieving such imaging is presently state-of-the-art or in development.

Accelerator Production of Tritium

P-23 contributes to the APT program by supplying basic nuclear-physics data, performing integral tests of the calculated neutronic performance of benchmark systems, developing beam diagnostics, and participating in irradiation studies of components for this program. Basic nuclear physics data include neutron total and reaction cross sections and activation data, mostly measured with the spallation neutron source at WNR. Integral tests employ small-scale mockups of the accelerator target and the neutron-reflecting blanket. These allow the initial neutron production, the final tritium production, and intermediate steps to be quantified and compared with calculations. Beam diagnostics use P-23's imaging capabilities. These data-measurement activities and integral demonstrations are continuing as the APT program progresses.

Nuclear Research

Compound nuclear states provide an excellent laboratory for studying violation of basic symmetries because of enhancements of the effect of parity violation in this system that are of order 10^7. The origin of these enhancements is a combination high-level

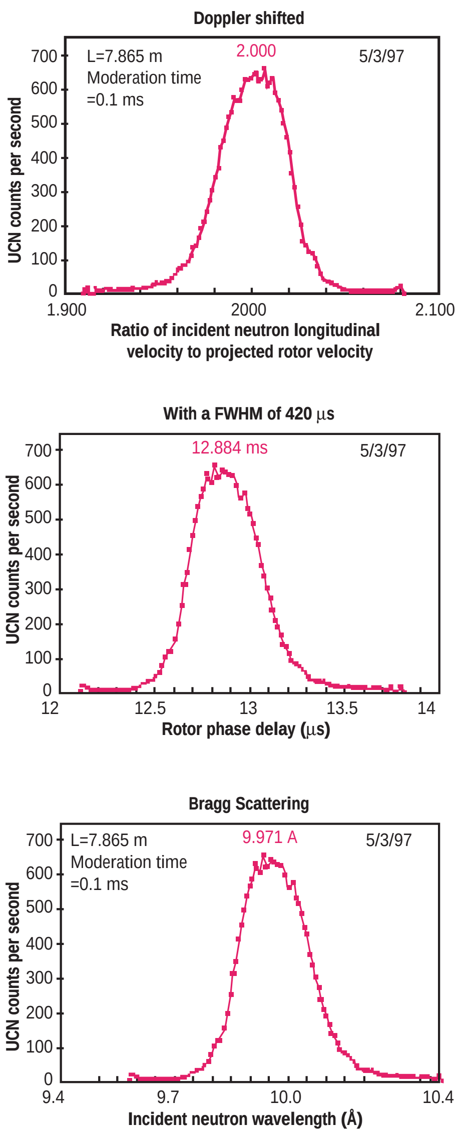


Fig. 2 Conditions and results for the UCN rotor reflector experiments. Thirty UCN per pulse were detected when the rotor was within 90 µs of the center. Slow neutrons generated with the rotor reflector system will be used to investigate the radioactive decay of free neutrons.

density and large difference between *s*-wave and *p*-wave neutron widths. This width difference enhances the effects of parity violation because we observe mixing of large *s*-wave resonances into small *p*-wave resonances. In the past we have observed parity violation in neutron resonance reactions for a large number of resonances in more than a dozen target isotopes. With techniques developed by P-23 and our partners, we identified very weak p-wave resonances where parity violation can occur and be observed with amplitudes of up to 10% of parity-conserving interactions. Nuclear theory predicted that the sign of the parity-violating effect should be random, and for all but one nucleus it appears to be. The exception is thorium-232 (^{232}Th), where the violation for the eight resonances with the strongest effects are all of the same sign, which would have a less than 0.25% probability of occurring if the sign were indeed random. We have investigated all of the readily available isotopes at maxima in the p-wave strength function and therefore are bringing this research to a close. The case of ^{232}Th remains an enigma. As a follow-on to our work in parity violation in heavy nuclei, we are developing an experiment to measure parity violation in the *np* system. This experiment will attempt to measure the asymmetry in gamma rays emitted after capture of polarized neutrons by protons in a liquid-hydrogen target. The experiment will be conducted at the MLNSC, and the shuttle, beam guides, and apparatus are currently in design.

We are also active in other tests of fundamental symmetries in the beta decay of trapped atoms and of free neutrons. Sensitive tests of the parity-violating beta-spin asymmetry correlation in the decay of rubidium-82 (^{82}Rb) constitute one experimental sequence that we anticipate will yield results with a precision one order of magnitude greater than any previous experiment (see the detailed research highlight on this topic in Chapter 2). In studies of the decay of the free neutron, we initiated the EMIT (“time” reversed) collaboration to pursue a search for time-reversal invariance violation. For this we have designed an experiment that promises to be seven times more sensitive than previous experiments. We have also proposed an experiment to measure the beta asymmetry in the beta decay of polarized ultracold neutrons (UCN).

UCN were first produced at LANSCE in 1996 by the use of a rotor reflector (Fig. 2). These neutrons travel with speeds of less than 8 m/s. We are continuing to develop this source with improved cold moderators and better rotor reflectors. We plan to use this source to test the key concepts in an experiment to measure the radioactive decay of free neutrons. We are also doing research and development aimed at an experiment to measure the neutron electric dipole moment using UCN produced and stored in a bath of superfluid ^{4}He. Both of these measurements aim at detecting physics beyond the standard model of strong and electroweak interactions. We are also studying the feasibility of a cryogenic source of UCN to be operated as a stand-alone spallation UCN source. Preliminary indications are that such a source, using only a few percent of the LANSCE proton beam, could provide the world’s most intense source of UCN. Such a world-class source of UCN at LANSCE would open up new opportunities for experiments in fundamental physics and the possibility of novel applications to materials science.

Another area in basic nuclear research is the Milagro project (see Fig. 1). Very high-energy gamma rays from the cosmos can be detected when they enter the atmosphere and produce an air shower of particles. The Milagro project, located in the Jemez Mountains above Los Alamos, involves the construction and operation of a high-efficiency observatory for gamma rays in the energy range around 10^{14} eV. This observatory is a joint project of Los Alamos and a large number of universities. It will be especially well-suited for the study of episodic or transient gamma-ray sources—that is, for recording gamma-ray bursts. It is operational 24 hours a day, 365 days a year, and its field of view is nearly half of the sky. A small scale version of Milagro, Milagrito, operated in 1998. The full-scale detector is presently being assembled.

We are also involved in ongoing research of solar neutrinos. The number and spectrum of neutrinos from the sun continues to challenge our understanding of solar physics and neutrino properties. For many years we have been working with scientists from the (former) Soviet Union to detect neutrinos by using large quantities of gallium far underground in the Caucasus Mountains. This lengthy study, known as the SAGE (Soviet-American Gallium Experiment) collaboration, has revealed that the number of neutrinos detected is about half of that predicted by the best solar and neutrino models. Now we are collaborating in the development of SNO, a neutrino observatory more than a mile underground in Sudbury, Ontario. The SNO detector will soon be operational and consists of an acrylic vessel holding 1,000 tonnes of heavy water surrounded by another vessel with 8,000 tonnes of light (regular) water. All three flavors of neutrinos (electron, muon, and tau) will be detected. Development of this detector includes the design and fabrication of very-low-background ^{3}He detectors and new electronics. As a spin-off, the very sensitive, low-background detectors developed for the observatory will be used to screen high-density microelectronics for trace radioactive contaminants that can cause computer errors by “flipping” bit patterns. The physical structure has been completed, and the vessel is being filled with water. The first ^{3}He detectors have been tested underground at Sudbury, and they perform as expected. We expect to complete construction and have all counters underground by summer 1999.

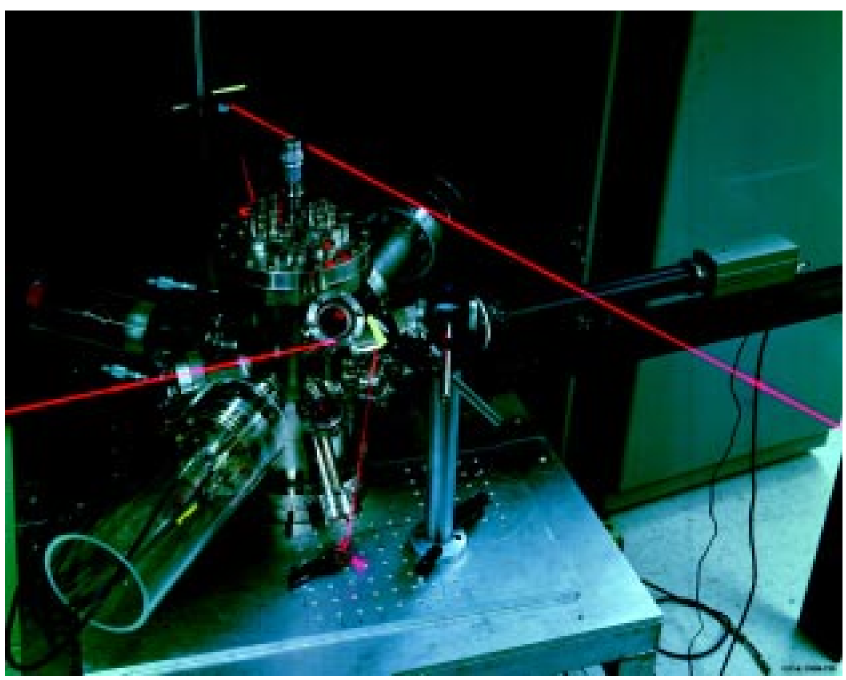
Applications of Basic Research

Quantum computation, a field in its infancy, promises a new approach to solving some problems (regarded as intractable in classical computation) by using the quantum-mechanical superposition of many states (numbers) at once. To realize such a computer, we are developing a system with cold, trapped atoms that represent the quantum-mechanical states. Quantum logical operations are performed with laser manipulations of the states of the trapped atoms (Fig. 3). Using conventional lasers, we have recently succeeded in trapping and imaging calcium ions that have the required spectroscopic structure to allow them to serve as basic quantum-mechanical bits. We are developing advanced diode lasers to perform the same operation, but with much reduced power requirements and cost.

Our applied research also includes work in quantum cryptography, which is covered in a detailed research highlight in Chapter 2. Quantum mechanics provides an approach to unbreakable cryptographic codes that not only can transmit the code "key" with security but that can also reveal the presence of eavesdropping. We have demonstrated this quantum cryptography over 48 km of fiber-optic cable and are developing longer transmission demonstrations. In a related effort, we have demonstrated transmission of a "key" through 200 m of air, and through this technology we are aiming at establishing secure communications between ground-based stations and low-Earth-orbit satellites.

We are also carrying out fundamental studies in "interaction-free measurements." Using the complementary wave- and particle-like nature of light, it is possible to determine the presence of an object without any photons being absorbed or scattered by it. Based on

Fig. 3 ***Apparatus for manipulating the states of cold, trapped atoms. Using such a system, we have succeeded in trapping and imaging calcium ions that have the required spectroscopic structure to allow them to serve as basic quantum-mechanical bits for quantum computation.***



these studies, we have begun investigating the practical implementation of "interaction-free imaging," where the techniques are used to take a pixellated image of an object, again with the goal of negligible absorption or scattering; at present, a resolution of better than 10 μm has been achieved, and we hope to reduce this even further. This work is covered in a detailed research highlight in Chapter 2.

We also support DOD programs in mine detection and seeker applications. For the detection of land mines, we are investigating the use of neutrons as an interrogating probe, with the detection of the resulting activation gamma rays as the positive signature. High-intensity neutron sources are necessary for the required sensitivity, and we are developing them in collaboration with other groups. Accelerator sources are strongly preferred because their energy can be tuned and specified, and they can be turned off when not in use. We are assessing the required sensitivity of detection, using our extensive experience acquired in developing neutron detectors for the Nuclear Test Program and for accelerator-based experiments. P-23 has also developed a laser-based, range-gated imaging system for the airborne detection of submerged mines. The system has undergone testing in both controlled-tank and open-sea environments. We have supported seeker (target identification) programs with range-gated laser distancing and ranging (LADAR) experiments carried out at the Wright Laboratory's laser range at Eglin Air Force Base. These experiments are part of a joint DOE/DOD technology-development program.

Further Information

To learn more about the projects described here, as well as other projects within P-23, refer to the project descriptions in Chapter 3. Some of our major achievements are also covered as research highlights in Chapter 2, as mentioned above. These include our work in quantum computation, interaction-free measurement, free-space quantum key distribution, and fundamental symmetries with magnetically trapped ^{82}Rb.